ANNALS OF GEOPHYSICS, Fast Track 2, 2014

Intercomparison of Metop-A SO_2 measurements during the 2010-2011 Icelandic eruptions

Maria Elissavet Koukouli[1*], Lieven Clarisse[2], Elisa Carboni[3], Jeroen van Gent[4], Claudia Spinetti[5], Dimitris Balis[1], Spyros Dimopoulos[1], Roy Grainger[3] , Nicolas Theys[4], Lucia Tampellini[6] and Claus Zehner[7]

1 Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, Greece, 2 Université Libre de Bruxelles, Brussels, Belgium, 3 COMET, Atmospheric, Oceanic & Planetary Physics, Oxford University, Oxford, UK, 4 Belgian Institute for Space Aeronomy, Brussels, Belgium, 5 Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, 6 Compagnia Generale per lo Spazio, Milano, Italy, 7 European Space Agency, Rome, Italy.

*mariliza@auth.gr

Abstract

The European Space Agency project Satellite Monitoring of Ash and Sulphur Dioxide for the mitigation of Aviation Hazards, was introduced after the eruption of the Icelandic volcano Eyjafjallajökull in the spring of 2010 to facilitate the development of an optimal End-to-End System for Volcanic Ash Plume Monitoring and Prediction. The Eyjafjallajökull plume drifted towards Europe and caused major disruptions of European air traffic for several weeks affecting the everyday life of millions of people. The limitations in volcanic plume monitoring and prediction capabilities gave birth to this observational system which is based on comprehensive satellite-derived ash plume and sulphur dioxide [SO_2] level estimates, as well as a widespread validation using supplementary satellite, aircraft and ground-based measurements. Inter-comparison of the volcanic total SO_2 column and plume height observed by GOME-2/Metop-A and IASI/Metop-A are shown before, during and after the Eyjafjallajökull 2010 eruptions as well as for the 2011 Grímsvötn eruption. Co-located ground-based Brewer Spectrophotometer data extracted from the World Ozone and Ultraviolet Radiation Data Centre for de Bilt, the Netherlands, are also compared to the different satellite estimates. Promising agreement is found for the two different types of instrument for the SO_2 columns with linear regression coefficients ranging around from 0.64 when comparing the different instruments and 0.85 when comparing the two different IASI algorithms. The agreement for the plume height is lower, possibly due to the major differences between the height retrieval part of the GOME2 and IASI algorithms. The comparisons with the Brewer ground-based station in de Bilt, The Netherlands show good qualitative agreement for the peak of the event however stronger eruptive signals are required for a longer quantitative comparison.

I. INTRODUCTION

The main objective of the European Space Agency [ESA] *Satellite Monitoring of Ash and Sulphur Dioxide, SO_2, for the mitigation of Aviation Hazards,* SACS-2/SMASH, project is the development, improvement and validation of satelite-derived ash & SO_2 products. This system is based on improved and dedicated satellite-derived ash plume and sulphur dioxide level assessments following the Support to Aviation Control Service (SACS, http://sacs.aeronomie.be), which is a free online service initiated by ESA for the near-real-time satellite monitoring of volcanic plumes of SO_2 and ash [Brenot et al., 2014]. The SACS-2/SMASH system has been comprehensively validated using auxiliary satellite, aircraft and ground-based measurements [Koukouli et al., 2014; Spinetti et al., 2014.]. This paper provides inter-comparisons between three different SO_2 column and plume height assessments from two different satellite instruments for the 2011 Grímsvötn eruption. The satellite SO_2 products are further being compared to ground-based SO_2 column observations for the Eyjafjallajökull 2010 eruptions.

II. SO_2 OBSERVATIONS AND METHODOLOGIES

I. IASI SULPHUR DIOXIDE PRODUCTS

The hyper-spectral Infrared Atmospheric Sounding Interferometer (IASI) was launched in October 2006 onboard the Meteorological Operational satellite-A (MetOp-A) [Clerbaux et al., 2009] for meteorological and scientific applications. Global nadir measurements are acquired twice a day at 09:30 and 21:30 mean local equatorial time with a 12 km radius footprint in the nadir. In the following analysis two IASI SO_2 products are used: one developed by the Atmospheric Spectroscopy group of the Université Libre de Bruxelles, hereafter *ULB*, and one developed by the Earth Observation Data Group at the University of Oxford, hereafter *Oxford*. Both products use similar algorithms for the detection [Clarisse et al., 2014] and retrieval of total columns [Carboni et al., 2012] however the Oxford algorithm retrieves the SO_2 plume height simultaneously with the SO_2 column amount, which has the advantage of yielding realistic error estimates. The ULB algorithm retrieves the height prior to the column and has the added benefit of not relying on any a-priori information.

II. GOME2 SULPHUR DIOXIDE PRODUCTS

The second Global Ozone Monitoring Experiment (GOME-2) is a UV/visible nadir-viewing spectrometer covering the 240-790 nm wavelength interval with a spectral resolution of 0.2 – 0.5 nm [Munro et al., 2006] also on board the MetOp-A satellite. Its ground pixel size is nearly constant along the orbit, around 80 x 40 km². The GOME-2 SO_2 products shown in the analysis have been developed at the Belgian Institute of Space Aeronomy, (hereafter *BIRA-IASB*) and were derived with an extended version of the GODFIT trace gas column retrieval algorithm [Lerot et al., 2010]. The algorithm derives the SO_2 total column amount and effective plume height simultaneously by applying an iterative direct fitting method with an optimal estimation inversion scheme. *A priori* information is only used for the SO_2 plume height.

III. BREWER SULPHUR DIOXIDE COLUMNS

Measuring total SO_2 column using Brewer instruments is discussed in Kerr et al., [2007], and references therein. Brewer spectrophotometers measure the UV absorption spectrum at five wavelengths. Once the ozone column is calculated, the total SO_2 column can be determined using semi-empirical equations based on the measured light intensity at each of the wavelengths, equivalent extraterrestrial light intensities, the air mass factor, the pre-calculated column amount of ozone and the absorption coefficients of the two interfering species. Since the signal-to-noise level for the SO_2 absorption is usually quite low, very well calibrated instruments are required to monitor nominal SO_2 levels. To the best of our knowledge, no comprehensive error assessments of the Brewer total SO_2 columns have been reported as yet. After imposing a rigorous quality control on the stations reporting Brewer SO_2 columns available through the World Ozone and Ultraviolet Radiation Data Centre (WOUDC), [Koukouli et al., 2014], a total of 16 European stations were accepted as possibly being able to show signs of increased SO_2 levels due to the volcanic eruptions. In extreme cases, such as volcanic eruptions [Fioletov et al., 1998], SO_2 levels typically rise well above instrumental noise permitting their comprehensive study using the Brewer instrument. Flentje et al., [2010], showed enhanced atmospheric levels during the Eyjafjallajökull eruptive period using the Brewer observations at Hohenpeissenberg, Germany, and Rix et al., [2012], report good comparisons between GOME-2/Metop-A measurements and ground-based findings at Valentia, Ireland for the May 2010 events. Here, we show comparisons over de Bilt, The Netherlands, one of the few European locations that where substantial plume drifted over.

III. Results

In Figure 1 the SO_2 column amount of the three algorithms is compared for May 23rd 2011; the SO_2 column amounts are gridded on a regular grid of 0.25 x 0.25 deg latitude/longitude to account for the differences in footprint. Note that this is the first time the different retrieval schemes and findings are compared as such. The ULB/IASI results are shown on the left, the Oxford/IASI in the middle and the BIRA-IASB/GOME-2 in the right column. No cut-offs/flags were used as part of a quality screening of the data since such a screening eliminates pixels with high SO_2 amounts in the central denser part of the plume. For aviation applications, such a strict quality control is not needed, as long as SO_2 is reliably detected. The results shown are very promising with all three algorithms capturing quite well both the magnitude of the loading as well as the central location of the plume to the NW of Iceland and its dispersion over the North Atlantic Sea. For the 190 common grids between the Oxford and ULB/IASI results, the mean SO_2 loading estimated by the Oxford algorithm is 14.32±25.14 D.U. and by the ULB algorithm at 11.76±16.60 D.U. with a correlation coefficient of 0.85 for the two algorithms. For the 232 common grids between the BIRA-IASB/GOME-2 and the ULB/IASI results, the mean SO_2 loading estimated by GOME-2 is 9.06±14.33 D.U. and by IASI 10.96±15.15 D.U. with a correlation of 0.64. For the 173 common grids between the BIRA-IASB/GOME-2 and the Oxford/IASI results, the mean GOME-2 loading is 10.97±15.68 D.U. and the mean IASI loading is 16.52±28.60 D.U. with a correlation of 0.64. In Figure 2 the SO_2 plume height estimated for the 23rd of May 2011 from the IASI and GOME-2 observations is shown. All three retrievals show a well-defined plume, setting off in a westerly direction over Iceland before rising North- and Eastwards, resembling an arm over the Arctic Sea. Since for small amounts of SO_2, there is not enough information inherent in the measured spectra in order to retrieve an independent altitude value, the resultant height values will tend towards the a priori values. For Oxford/IASI the retrieval is performed in a pressure grid and the plume height a priori values is set to 400mbars (~6km) and the a priori error to 1000 mbars. In the BIRA-IASB/GOME-2 algorithm the *a priori* height error was set to 5km and so any *a posteriori* height error value that approaches the *a priori* error levels signifies non-dependable detection. No screening was applied to either IASI data whereas a minimum amount of four degrees of freedom was permitted for the BIRA-IASB/GOME2results in order to signify meaningful plume height detection. As can be noted in the Figure, significant differences exist among the IASI and the GOME-2 assessments of the plume height. In numbers, for the 173 common grids, the mean GOME-2 plume height is found at 7.15±0.84 km and the mean Oxford/IASI plume height at 8.82±2.0 km; for the 232 common points, the mean GOME-2 plume height is at 7.12±0.95 km and the mean ULB/IASI height at 9.40±1.44 km. For the comparison between the two IASI algorithms, the 190 points provide a mean ULB/IASI height of 9.00±2.00 km and the Oxford/IASI of 8.17±2.64 km with a good correlation of R-squared 0.62. The agreement between the two algorithms is valid for the entire European domain and not solely on the location of the maximum plume load and height. In Figure 3, the comparisons between satellite and ground-based SO_2 amounts in the days before, during and after the Eyjafjallajökull 2010 events [grey shaded areas] are shown for the De Bilt Brewer spectrophotometer in The Netherlands. The Oxford/IASI product is shown in the left plot and the ULB/IASI product in the right. The ground-based daily mean Brewer data are shown in red, the instantaneous daytime [nighttime] satellite observations in light blue [light green] and the satellite daily mean in black. Since only four co-locations were found for the BIRA-IASB/GOME-2 within a 200km radius and no time imposition, only the two IASI comparisons are presented. The comparison is quite good for the two IASI products with the levels rising equivalently between satellite and ground data for the highly loaded days after the eruption, reaching daily maxima around 2-3 D.U., well above instrumental noise.

IV. Discussion

In this paper, a few representative examples of the validation activities performed within the SACS-2/SMASH, European Space Agency project have been presented. SO_2 column loading and plume height extracted using three different algorithms analysing Metop-A observations by the IASI and GOME-2 instruments during the 15 to 26 April 2010 and 4 to 20 May 2010, Eyjafjallajökull, Iceland, eruptions and the 23rd of May 2011, Grímsvötn, Iceland, eruption are shown.

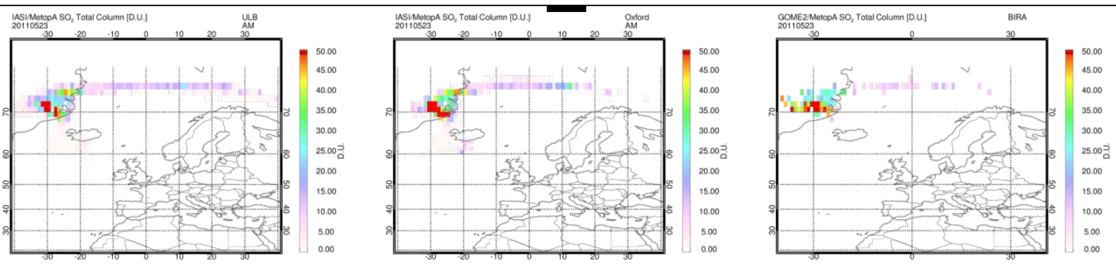

Figure 1: *Estimated total atmospheric SO_2 load over Europe on May 23rd 2011 as seen by the ULB/IASI algorithm [left], the Oxford/IASI algorithm [middle] and the BIRA-IASB/GOME-2 algorithm [right].*

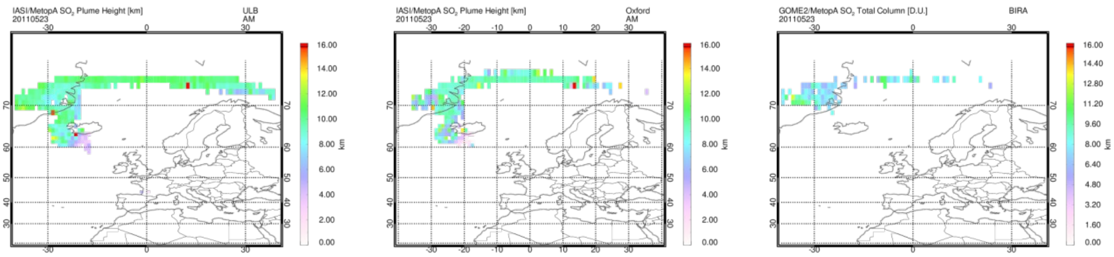

Figure 2: *Estimated total SO_2 plume height over Europe on May 23rd 2011 as deduced by the ULB/IASI algorithm [left], the Oxford/IASI algorithm [middle] and the BIRA-IASB/GOME-2 algorithm [right].*

Taking into consideration substantial differences in instrumentation, algorithm, wavelength range, spatiotemporal resolution, and so on, the three algorithms are providing consistent results depicting well the central plume location as well as its dispersive patterns. A highly satisfactory agreement, with correlations ranging between 0.64 and 0.85, is found for the comparisons of the SO_2 loading during the chosen Grímsvötn day; the plume height concordance provides a far greater challenge with the two IASI algorithms agreeing adequately both in location and in height, however the GOME-2 results show a more uniform plume height across the domain and also seem not to be able to depict the plume height near the source. The IASI/MetopA comparisons with a ground-based station in de Bilt, The Netherlands, are also promising but would benefit greatly from a far larger statistical sample during a stronger eruptive occasion. We hence conclude that all three Metop-A SO_2 products are mature enough to be used in a satellite volcanic monitoring system with possible improvements. As a side note, it is equally important to assess whether SO_2 may act as proxy for volcanic ash during volcanic eruptions for an early warning system to prevent planes from potential encounters with volcanic plumes, sometimes not the case several hours after an eruption [Thomas and Prata, 2011.]

References

[Brenot et al., 2014] Brenot, H., et al., (2014), Support to Aviation Control Service (SACS): an online service for near-real-time satellite monitoring of volcanic plumes, Nat. Hazards Earth Syst. Sci., 14, 1099-1123.

[Carboni, et al., 2012] Carboni, E., et al., (2012), A new scheme for sulphur dioxide retrieval from IASI measurements: application to the Eyjafjallajökull eruption of April and May 2010 Atmos. Chem. Phys., 12, 11417-11434.

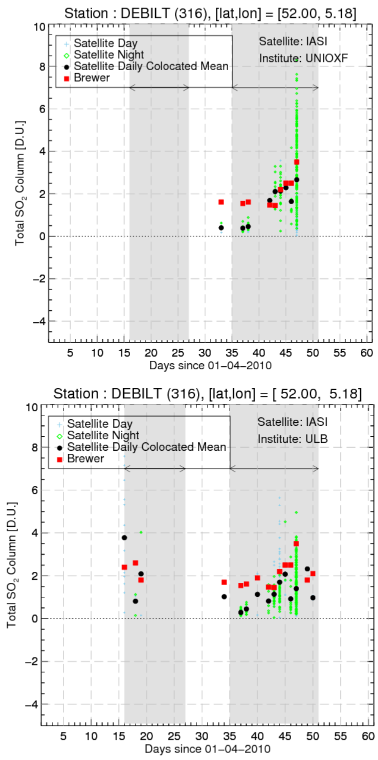

Figure 3: *Total SO_2 load over De Bilt, The Netherlands. Details in the text.*

[Clarisse, et al., 2014] Clarisse, L., et al. (2014), The 2011 Nabro eruption, a SO_2 plume height analysis using IASI measurements. Atmos. Chem. Phys., 14, 3095-3111.

[Clerbaux, et al., 2009] Clerbaux, C., et al. (2009), Monitoring of atmospheric composition using the thermal infrared IASI/MetOp sounder, Atmos. Chem. Phys., 9, 6041-6054.

[Fioletov, et al., 1998] Fioletov, V. E., et al. (1998), Influence of volcanic sulfur dioxide on spectral UV irradiance as measured by Brewer Spectrophotometers, Geophys. Res. Let., 25, (10), 1665-1668.

[Flentje, et al., 2010] Flentje, H., et al. (2010), The Eyjafjallajökull eruption in April 2010 – detection of volcanic plume using in-situ measurements, ozone sondes and lidar-ceilometer profiles, Atmos. Chem. Phys., 10, 10085-10092.

[Kerr and Davis, 2007] Kerr, J. B., and Davis J. M. (2007), New methodology applied to deriving total ozone and other atmospheric variables from global irradiance spectra, J. Geophys. Res., 112, D21301.

[Koukouli. et al., 2014] Koukouli, M. E., et al. (2014), SACS-2/SMASH Validation Report on the Eyjafjallajökull & Grímsvötn Eruptions, http://sacs.aeronomie.be/Documentation/index.php, last accessed: January 23th, 2015.

[Lerot, et al., 2010] Lerot, C., et al. (2010), The GODFIT algorithm: a direct fitting approach to improve the accuracy of total ozone measurements from GOME, Int. J. Remote Sensing, 31, 543-550.

[Munro, et al., 2006] Munro, R., et al. (2006): GOME-2 on MetOp, in: Proc. of The 2006 EUMETSAT Meteorological Satellite Conference, Helsinki, Finland, EUMETSAT, p. 48, ISBN 92-9110-076-5.

[Rix, et al., 2012] Rix, M., et al. (2012), Volcanic SO_2, BrO and plume height estimations using GOME-2 satellite measurements during the eruption of Eyjafjallajökull in May 2010, J. Geophys. Res., 117.

[Spinetti, et al., 2014] Spinetti, C., et al. (2014), Volcanic SO_2 by UV-TIR satellite retrievals: validation by using ground-based network at Mt. Etna, Annals of Geophysics, this issue.

[Thomas and Prata, 2011] Thomas, H.E. and Prata, A. J. (2011), Sulphur dioxide as a volcanic ash proxy during the April–May 2010 eruption of Eyjafjallajökull Volcano, Atmos. Chem. Phys., 11, 6871–6880.